Superconducting rectifier based on the asymmetric surface barrier effect

D. Y. Vodolazov[1,2] and F. M. Peeters[1,*]
[1]*Departement Fysica, Universiteit Antwerpen, B-2020 Groenenborgerlaan 171, Antwerpen, Belgium*
[2]*Institute for Physics of Microstructures, Russian Academy of Sciences, 603950, Nizhny Novgorod, GSP-105, Russia*
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The rectifier consists of a superconducting strip placed in an external perpendicular magnetic field. By roughing one of the edges parallel to the current the conditions for vortex entry become different on both edges of the sample. An advantage of this device is that the sign of the rectified signal is determined by the direction of the applied field. Our estimates show that the rectifying effect in such a structure may be observed up to MHz frequencies and that it is able to rectify the currents up to ampere when using low temperature superconductors.

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During the past few years, several papers appeared with proposals of superconducting rectifiers based on the dynamics of vortices.[1–4] The main idea in these works is the creation of asymmetric potentials for the motion of vortices through microstructuring of the superconductor. In this Brief Report, we present a technically more simple approach based on the use of surface barriers[5] to rectify an ac superconducting current. In contrast to previous works, there is no need to create asymmetric potentials all over the superconductor. It is well known that the surface barrier effect leads to an increase of the value of the magnetic field[5] and the transport current[6–8] for which vortices are allowed to penetrate the sample. This is a consequence of the appearance of an energy barrier for the vortex entry. This effect was observed experimentally both in low and high temperature superconducting materials.[9–12] It was also shown that surface and/or edge defects suppress this surface barrier, but that they are not able to eliminate it completely.[13–16] Calculations show that such surface and/or edge defects may decrease the critical current or critical field for the first vortex entry, with a maximum reduction by $\sqrt{\kappa}$ (κ is the Ginzburg-Landau parameter) in the case of bulk superconductors with the size of the defect larger than the London penetration depth λ.[13–15] It is possible to show that for thin superconducting films with thickness $d<\lambda$ this suppression is enhanced, but it cannot be larger than $\sqrt{\kappa_{eff}}$ ($\kappa_{eff}=\kappa\lambda/d$).

We consider a superconducting strip with relatively good edges and suppress the surface barrier on one edge by introducing artificial defects (see insert in Fig. 1). The most simple way to account for the surface barrier effect is to use the model proposed in Ref. 6 (which is also valid when surface and/or edge defects are presented in the superconductor[17]). In this model, one assumed that vortices can enter the sample only if the current density at the edge is equal to the critical value j_s. Based on this model,[12] an analytical expression for the critical current was obtained for a thin superconducting film of arbitrary width in the case of identical edges

$$I_c(H) = \begin{cases} I_c(0)(1 - H/H_s), & 0 < H < H_s/2, \\ I_c(0)H_s/4H, & H > H_s/2, \end{cases} \qquad (1)$$

with $I_c(0)=j_s d\sqrt{\lambda_\perp W/\beta}$ the zero magnetic field critical current, $H_s=2j_s d\sqrt{\beta\lambda_\perp/W}$ is the field at which the first vortex penetrates the sample, $\lambda_\perp=\lambda^2/d$ is the effective penetration depth in thin superconductors and $\beta=1/2\pi+\lambda_\perp/W$.

It is not difficult to generalize these results to the case of a film with different edges. The easiest way to understand this is through graphical illustration. In Fig. 1, we present $I_c(H)$ as obtained for the case with different vortex entry conditions: j_{s1} and $j_{s2}=j_{s1}/2$ simulating the difference in surface barrier height at the left and right edge of the sample. This result can be easily constructed as follows. For two perfect flat edges where $j_s^{left}=j_s^{right}=j_{s1}$ we obtain symmetric dashed curve. When we make the two edges rough the critical current density reduces, and as a example we take $j_s^{left}=j_s^{right}=j_{s2}$, which results in the dotted curve shown in Fig. 1. In the case of asymmetric edges where only one edge is made rough, we obtain the mixed result presented by the solid curve.

To understand why the maximum of $I_c(H)$ may shift away from the $H=0$ line, we show in Fig. 2 the spatial dependence of the current density for some critical currents and different magnetic fields. For $H=0$, the current density distribution is

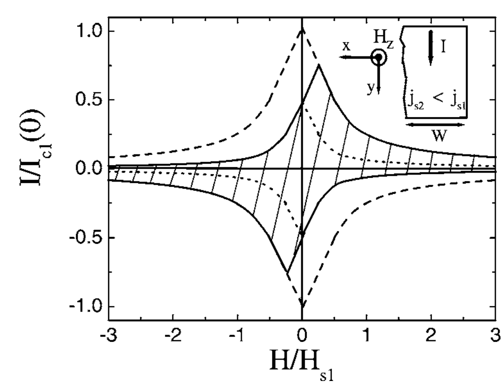

FIG. 1. Dependence of the critical current of the superconducting strip on the applied magnetic field. The dashed (dotted) curve corresponds to a strip with identical vortex entry conditions on both right and left edges: $j_s^{right}=j_s^{left}=j_{s1}$ ($j_s^{right}=j_s^{left}=j_{s2}=j_{s1}/2$). Solid curve is for asymmetric surface barriers: $j_s^{right}=j_{s1}$, $j_s^{left}=j_{s2}$. The inset depicts our device schematically.

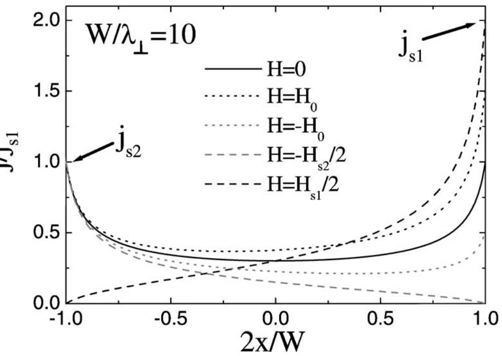

FIG. 2. Current distribution over the width of the film with asymmetric vortex entry conditions at different values of the magnetic field and for a current equal to the critical one. H_0 is some value chosen in the range $(0, H_{s2}/2)$.

symmetric [see Eq. (2) in Ref. 12] and the critical current is defined by $min(j_{s1}, j_{s2})$. If we apply a positive magnetic field $H_0 < H_{s1}/2$, the current density at the left side will decrease but it increases at the right side. Because at the right side, we still have $j_{edge} < j_{s1}$, we can still increase the current before the condition for vortex entry is satisfied at the left side. As a result the critical current will increase with H. It will increase up to some H^* at which the current density at the right edge becomes equal to j_{s1}. For $H > H^*$, the $I_c(H)$ will decrease with increasing H. For $0 \leqslant H < H^*$, the critical current is limited by j_{s2} at the left side, while for $H > H^*$, it is limited by j_{s1} at the right side. If we change the sign of the magnetic field, I_c starts to decrease already from $H=0$ because such a field increases the current density on the left edge and decreases it on the right one, i.e., I_c will follow the result for symmetric rough edges with $j_s^{left} = j_s^{right} = j_{s2}$.

For any nonzero value of the magnetic field, the critical current (current at which a voltage appears in the sample) depends on the direction of current flow. Choosing the working point (by changing the value of the magnetic field), we may find a regime where rectification of an ac superconducting current is possible for a given amplitude of the injected current. Using a simple model[18] for the current voltage characteristic,

$$V = \begin{cases} 0, & I < I_c(H), \\ (I^2 - I_c(H)^2)/I, & I > I_c(H), \end{cases} \tag{2}$$

and Eq. (1), we can plot in Fig. 3 the dependence of the time averaged voltage $\langle V \rangle$ on the amplitude I_{ac} of the ac signal $I(t) = I_{ac}\sin(t)$ and applied magnetic field H in the z direction.[19] Note that *qualitatively* the behavior of $\langle V \rangle$ (I_{ac}) is very similar to those found for superconducting ratchet systems.[1–4] There is no rectifying effect at small amplitudes of the ac signal, it rapidly increases and then decreases for $I \gg I_c$. The quantitative details very strongly depend on the explicit dependence of $V(I)$ and may vary from superconductor to superconductor.

To estimate the efficiency of such a rectifier, we use parameters typical for MoGe films. This material has quite low depinning current density (about 10^3 A/sm^2) and a pronounced edge barrier effect.[12] The critical current density j_s

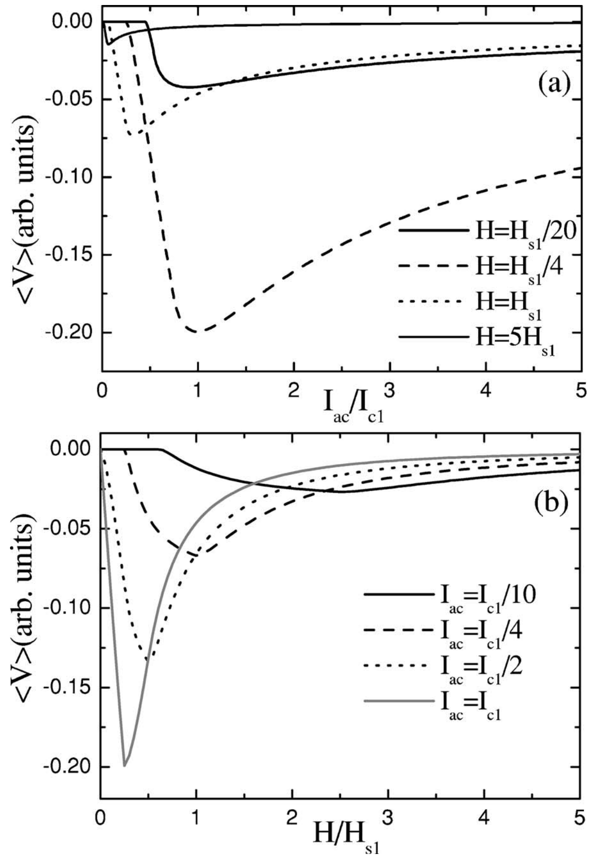

FIG. 3. Dependencies of the rectified voltage $\langle V \rangle$ (in arbitrary units) on the amplitude of the ac current (a) and applied magnetic field (b).

is about 2×10^6 A/sm^2 at $T = 4.2K$ and we chose the width $w = 1$ mm and thickness 400 nm. Because $\lambda(4.2K) = 650$ nm, the effective penetration depth in such a structure is $\lambda_\perp = \lambda^2/d = 1.12$ μm. For these parameters $I_c(0) \simeq 0.67$ A and $H_s \simeq 1.3$ Oe and at low magnetic fields such a MoGe rectifier with asymmetric surface barrier may rectify currents in the order of amperes.

In the magnetic field range $-H_{s2}/2 < H < H_{s1}/2$, the dependence $I_c(H)$ is linear (for positive currents). It implies that there are no vortices in the film for $I < I_c(H)$,[6,8] and hence, we can easily estimate the velocity of the penetrating vortices because they can be considered as independent moving objects. Using the expression for the vortex viscosity $\nu = 1.5\Phi_0 H_{c2}\sigma_n/c^2$ (Φ_0 is the magnetic flux quantum, σ_n is the normal conductivity, and H_{c2} is the second critical field) from Ref. 20 and the Lorentz force $F_L = j\Phi_0/c$ acting on the vortex, we obtain the time needed for the vortex to pass through the film

$$\langle t \rangle = \frac{w}{v} = \frac{1.5 H_{c2} w}{\langle j \rangle c \sigma_n}, \tag{3}$$

where $\langle j \rangle = \int_0^w j(x)dx/w$ is the average current density. For our parameters, we have $t \simeq 200$ ns. As a consequence, the rectifying effect for the considered film and the given range of magnetic fields should be observed for ac currents up to

MHz frequencies.[21] This frequency range can be increased if we decrease the width of the film, but at the same time, $I_{c1}(0)$ will also decrease. In any case, the maximal frequency cannot exceed $1/\tau_E$, where τ_E is the time relaxation of the nonequilibrium quasiparticle distribution in the superconductor. For low temperature superconductors, τ_E varies from 10^{-8} s for aluminium up to 10^{-10} s for tin and lead at temperatures close to the critical one.

In this respect, BiSCCO whiskers (cuprate superconductors with high quality crystal structure) with $\tau_E \simeq 10^{-12}$ s should be more suitable candidates. But unfortunately, in this material, the surface barrier is strongly suppressed by thermo-fluctuations. In general, in high temperature superconductors, there is only a weak influence of the surface barrier on the transport properties. The reason is that the surface barrier is rather low which is mainly due to the high anisotropy parameter[22] and the high temperatures which enhances the effect of fluctuations. This leads to a strong creep of the magnetic flux over the surface barrier.[23] In such materials, one should go to low temperatures in order to observe surface and/or edge barrier effects and, hence, to find the rectifying effect.

The edge and/or surface defects may be prepared litographically. This was done recently[24,25] for aluminium mesoscopic superconducting structures. It was shown that for an aluminium ring with a defect, the suppression of the critical field was 50% in comparison with a nondefective ring.[24] From a theoretical point of view, the most effective defects are those with length L much larger than the coherence length ξ and of width about ξ. It is possible to show that for such defects, the critical current density j_s should decrease as $1/\sqrt{L/\xi}$. Furthermore, the number of defects should be large enough in order to provide a noticeable voltage response.

We believe that the asymmetric surface barrier is responsible for the rectifying effect found in the work of Swartz and Hart about 40 years ago.[26] They found experimentally that rectification strongly depends on the quality of the surfaces and the largest effect was found when one of the surfaces was artificially damaged (covered by normal metal). Furthermore, when the magnetic field was applied parallel to the direction of the current no rectifying effect was found. It occurs because in this case, the magnetic field does not influence the current density distribution over the width of the sample and it practically corresponds to the case of $H=0$.

Bulk pinning of vortices may strongly affect the behavior we found due to surface rectification. In Ref. 27, the combined effect of bulk pinning and surface barrier on the critical current of a superconducting strip was studied. It turned out that while $j_p W d \ll I_c(0)$ (j_p is the pinning current density) the full critical current may be considered as a sum $I_c = j_p W d + I_c(H)$. For example, for MoGe films, corrections due to finite bulk pinning become important only at fields of about 10^3 Oe.[12]

To conclude, we like to point out that rectification due to asymmetric surface barriers should occur in any superconductor where vortices enter and exit the sample. Indeed it appears doubtful that real samples will have identical edges. Thus, vortices will more easily penetrate the superconductor from one edge than from another one. Such a rectified voltage can only be observed if it exceeds the voltage noise in the system. The studied mechanism in this paper may be the reason for the recently observed rectified voltage in superconducting Pb and Nb strips.[28] At least the qualitative dependence of $\langle V \rangle$ on the ac current amplitude and the magnetic field is reproduced by our mechanism. The found temperature dependence is still hard to understand, but may be a consequence of the fact that the relative length scale of the surface defects, i.e., $L/\xi(T)$, which influences the size of the asymmetry in the surface barrier, is temperature dependent.

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*Corresponding author. Electronic address: francois.peeters@ua.ac.be

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